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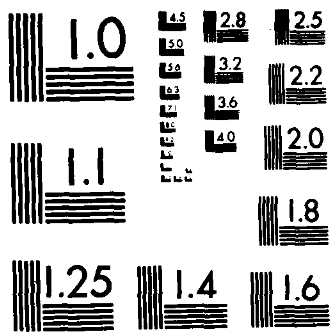

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THE MOVING THERMOACOUSTIC ARRAY

FINAL REPORT UNDER CONTRACT N00014-82-K-0425

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In the optoacoustic sound generation process, a laser beam is directed at the water surface to produce a controlled local reaction which, in turn, generates sound waves. At low optical intensities, the reaction is a linear thermal expansion of the medium; hence the term thermoacoustic source. Extremely high Doppler shifts are achievable by scanning the laser beam across the water. A theoretical model of the thermoacoustic source was developed that uses a time domain approach. Special attention was paid to the sonic and transonic

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conditions where high pressure transients can be generated which may have practical applications. It was found that the thermoacoustic conversion process was most efficient when the optical energy was delivered as an impulse train. The efficiency is fundamentally limited by the physical properties of the medium. The efficiency upperbound for sea water was found to be limited, and therefore a more efficient process was sought. It is expected that processes that are significantly more efficient may be found at higher laser intensities. Keywords: [illegible]

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I. INTRODUCTION

In the period 1 April 1982 - 30 September 1985, Applied Research Laboratories, The University of Texas at Austin (ARL:UT), has conducted research under Contract N00014-82-K-0425 to investigate both theoretically and experimentally the basic properties of a moving thermoacoustic source (MTS) and to evaluate its feasibility as a sonar source. The thermoacoustic process employs direct heating of the acoustic medium to produce a controlled local thermal expansion which, in turn, generates sound waves. The thermal energy is delivered by a laser beam to the water surface without any physical contact. The thermoacoustic source may be moved by deflecting the laser beam with a rotating mirror. The deflection causes the position of the thermal sound source to change as a function of time. This allows the signal to be Doppler shifted to a far greater degree than can be achieved with conventional sound projectors that have to be in physical contact with the acoustic medium.

The study has been pursued from two directions: a basic study of the fundamental physics of the process, and a feasibility study for sonar applications. These two studies are described in greater detail in Sections II and III. The feasibility study led to a preliminary study of the nonlinear optoacoustic process as an alternative, and potentially more efficient, mechanism for remote sound generation; this is described in Section IV. Detailed reports on these three activities are contained in Refs. 1-3. An overview of the accomplishments is as follows.

(1) Significant progress has been made in the basic investigations of the fundamental physical properties of the MTS. This part of the study was designed as a doctoral project leading to a Ph.D. degree (Yves Berthelot , supervised by Dr. Ilene J. Busch-Vishniac of the Department of Mechanical Engineering, The University of Texas at Austin). A theoretical model of the acoustic pressure wave generated by an MTS was implemented on a CYBER 830 computer. One of its features is the inclusion in the calculations of the effects of diffraction due to the finite laser beamwidth which are crucial to the case of a source moving at transonic velocities. The model is valid for subsonic, transonic, and supersonic source speeds and receivers in the nearfield or farfield. In parallel, a large amount of experimental data was taken and analyzed for different values of the parameters of

importance. Experimental results and theoretical predictions compare well except at near-sonic source velocities, where the measured levels are more than an order of magnitude higher than predicted. This suggests that the linear model is not valid for a near-sonic source.

(2) A theoretical feasibility study of the MTS for sonar applications, particularly the efficiency of the thermoacoustic conversion process, was made by Dr. Nicholas P. Chotiros assisted by Ms. Debora Offer. The study identified the upperbounds that are constrained by the physical properties of the medium and the energy output of the thermal source. The efficiency of the thermoacoustic process was found to be inadequate for normal sonar applications. This result, which is based upon the linear acoustic model, conflicts with other findings presented in this report, especially as it is applied to near-sonic source speeds. A new study is underway to address the special problem of a source moving at near-sonic speeds.

(3) It is expected that significantly more efficient processes may be found at higher laser intensities. These processes are generally nonlinear and often explosive. The higher laser intensities have been found experimentally by other researchers to be more efficient, but the processes are not well understood. To obtain higher efficiencies, an investigation of the nonlinear optoacoustic processes was initiated. Comparison of the model predictions with some existing experimental data showed reasonable agreement. A preliminary experimental investigation was made. The results were very encouraging and further work is planned.

II. BASIC STUDY OF THE MOVING THERMOACOUSTIC SOURCE

A. Introduction

The generation of sound by light was investigated experimentally more than one hundred years ago by Bell,[4] who came to the conclusion that "sonorousness, under the influence of intermittent light, is a property common to all matter." Bell's experiment resulted in the construction of a "photophone", or apparatus for the production of sound by light. Bell's invention of the photophone was neglected for many years, but recently it has received more attention because new developments in high power laser technology make this type of sound generation more suitable for practical applications. There is an obvious advantage to opto-acoustic generation of sound: it does not require the physical transducer to be in the medium. This unique property of laser induced sound has prompted intensive research in the past 20 years in various fields, such as nondestructive testing, molecular spectroscopy, and sonar applications. Tam[5] lists more than 400 references on laser-induced sound and Pierce's recent bibliography[6] on the same subject is more than 12 pages long.

There are several ways to produce sound with a laser. The most common mechanisms of optical to acoustic transduction are, in order of increasing efficiency, electrostriction, thermal expansion, surface evaporation, explosive boiling, and optical breakdown. Electrostriction is the result of polarization of molecules due to the electromagnetic input in the medium. The polarization of molecules induces changes in density and therefore produces sound which propagates in the medium. The thermal mechanism relies on heating of the medium by the laser. Changes in temperature produce changes in density and subsequently an acoustic wave. Surface evaporation may occur if the energy density of the laser at the point of impact on the medium is sufficiently high. In this case momentum transferred into the medium generates a sound wave. At even higher energy densities, it is possible to have gaseous bubble formation in the medium, and the collapse of the bubbles radiates noise. Finally, for extremely high laser energy densities, such as in the case of a focused high power laser, a very hot plasma is formed locally around impurities in the liquid and "rapidly expanding

cavities appear in the focal region, followed by shock wave propagation, cavity deceleration, localized cavitation, and eventual bubble collapse."[7] This is known as sound generation by optical breakdown. The earliest experimental detections of laser induced sound were reported in 1963.[8,9]

In this study, we restrict our attention to the specific mechanism of thermal expansion. A sound source which relies on heating of the medium by a light source is referred to as a thermoacoustic source (TS) or opto-acoustic antenna. Most thermoacoustic sources are created by shining a laser into a medium (usually water). The intensity of the laser is amplitude modulated at a fixed frequency so that it induces a periodic heating of the medium and therefore a fluctuation of density. This in turn generates an acoustic wave whose frequency is equal to the frequency at which the laser intensity is modulated. The wave equation describing the sound field of a lossless medium containing heat sources was first derived by Ingard.[10] A few years later Westervelt and Larson[11] showed theoretically that very directive sound beams of low frequency can be achieved by exploiting the thermoacoustic conversion of energy in water. The first experimental verifications of the directional properties of thermoacoustic sources were made by Muir, Culbertson, and Clynch,[12] who confirmed the validity of the theoretical model. As expected, the efficiency of the conversion of electromagnetic energy into acoustic energy was found to be very small (of the order of 10^{-8}) and they concluded that, "for potential applications of practical interest, ... megawatts of optical power would probably be required in the megahertz frequency region, with gigawatts of power required in the kilohertz region, and terawatts of power necessary in the low audio band." This low efficiency barrier was investigated in detail by Soviet physicists and they showed[13-15] that motion of the TS is expected to significantly increase the peak amplitude of the thermoacoustic signal, especially for a source moving at velocities close to the speed of sound. Such high source velocities are easily achieved experimentally. Since there is no physical transducer in the medium, drag force and flow noise are non-existent.

B. Objectives

The main objective of the present study is to investigate the basic physical properties of a laser induced TS and to extend the results to the case of a moving thermoacoustic source (MTS). Previous studies of MTS have been limited by experimental apparatus. They are also restricted to farfield radiation, and theoretical models generally break down when the MTS is moving at a velocity close to the speed of sound in the medium. The theoretical study is based on a new approach which provides information about the nearfield of a TS and about the acoustic signature when the source is moving at transonic velocity.

C. Achievements

The thermoacoustic mechanism of sound generation by a laser pulse beamed into water was investigated, both theoretically and experimentally, for both stationary and moving sources. The theoretical model is based on the linear Westervelt-Larson equation[11] describing thermoacoustic sound generation for an inviscid medium containing a heat source such as a laser beam in water. A time domain analysis was developed to find the pressure field radiated by the thermoacoustic source. The acoustic pressure was expressed as a convolution type summation between the impulse response of the system and the thermoacoustic source strength (time derivative of the laser intensity). The analysis is based on the impulse response of a stationary thermoacoustic source. Its geometry is shown in Fig. 1, in which a is the laser beam radius, r_0 and θ_0 are the distance and angle from the laser position at the water surface to the receiver, r is the distance from an arbitrary volume of irradiated fluid dV to the receiver, and r' is the distance from the image volume above the water surface to the receiver. Although this approach requires the use of a computer in most cases, it offers several advantages: (1) it is valid in the nearfield of the source and this has been verified experimentally, (2) it is also valid for any source velocity, because the Doppler shift associated with the motion of the source appears naturally within the "pseudo-convolution", (3) although the analysis presented here is restricted to the common case of a laser beam with a Gaussian cross-section intensity distribution, with an exponential shading along the beam penetration axis, the model can be

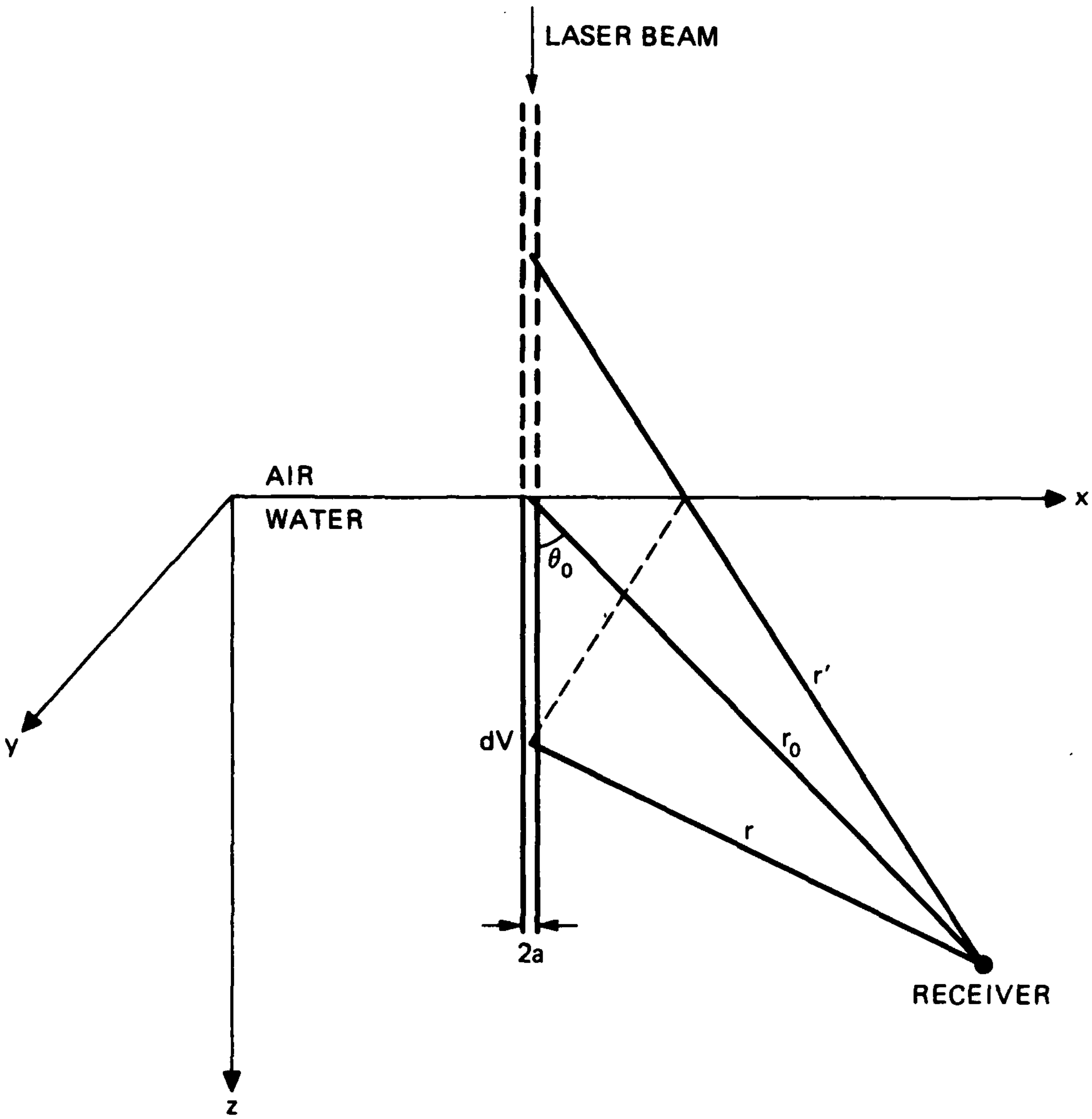

FIGURE 1
STATIONARY THERMOACOUSTIC SOURCE GEOMETRY

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extended to any laser intensity profile, (4) the impulse response of a thermoacoustic source is a useful tool in analyzing the acoustic response to thermoacoustic transient phenomena such as extremely short laser pulses or Mach waves produced by a laser beam moving at high velocity. It turns out that these transient signals are among the most promising ways to generate reasonably high peak pressure levels.

Experimental results were obtained with a laser system[16,17] providing up to 5 J of energy over a pulse duration of approximately 1 ms, during which the intensity was modulated at a single frequency between 5 and 80 kHz. Most of the experimental results were obtained with a Neodymium-Glass laser (optical wavelength 1.06 μm), so that the thermoacoustic source length in water was fairly short (~0.1 m).

Some experimental results are also given for the case of a long (~1 m) thermoacoustic source which was obtained by using a ruby laser (optical wavelength 0.6943 μm). The apparatus is shown in Fig. 2.

The main experimental results can be grouped into four categories: pressure waveforms, directivity patterns, sound level dependence on source velocity, and spreading curves. Source velocities up to Mach 2 were investigated with special attention to the case of transonic velocity. In general, the experimental results were in good agreement with theoretical predictions, and this confirms the validity of the Westervelt-Larson model even for supersonic velocities.

Finally, the Doppler shift of an acoustic source moving at transonic velocity was analyzed theoretically by taking into account the time dependence of the angle of observation between the source and the receiver. It was shown that this time dependence removes the singularity which occurs in the standard theory, when the source is moving at transonic velocity. It was also shown that, in the case of a line source, the transition between subsonic and supersonic regimes is a region where only wavelets coming from a certain part of the source are time inverted, whereas the rest of the wavelets are not. This partial time inversion suggests the possibility of reshuffling the wavelets in a signal, and this may have some

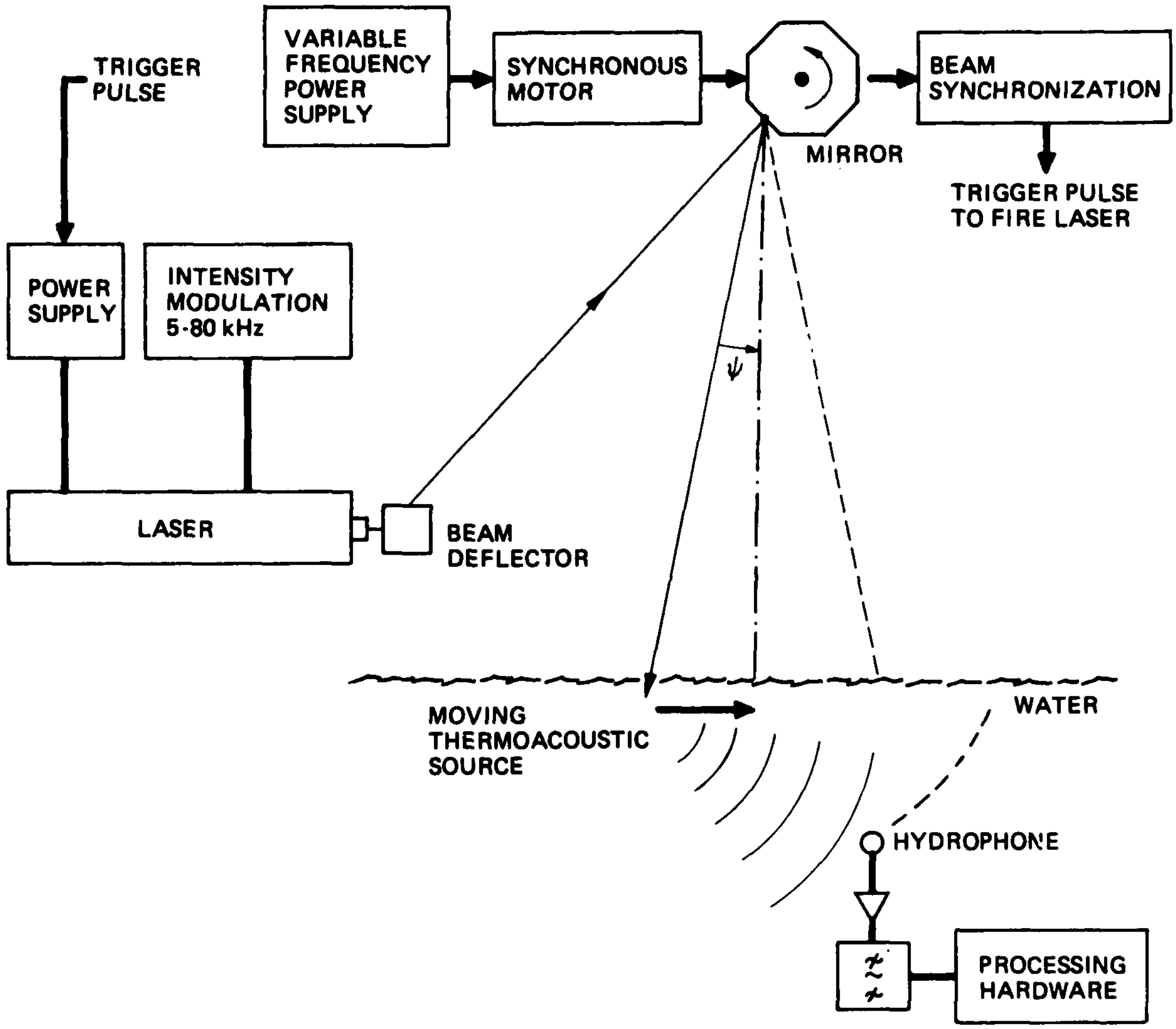

FIGURE 2
BLOCK DIAGRAM OF EXPERIMENTAL SYSTEM

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applications in signal coding. Future work on this topic should also include diffraction effects due to the finite size of the source, and non-rectilinear motion of the source to analyze path curvature, source acceleration, caustics, and focusing effects.

The results reported in this study show that, in general, the experimental results are in good agreement with the theoretical predictions. The major discrepancy was found to be that the theoretical model underestimates by a significant amount the measured acoustic level when the source is moving at transonic velocity. An example of the experimental results, obtained at a laser modulation frequency of 25 kHz, is shown in Fig. 3, in which the measured and predicted acoustic peak pressures, as a function of Mach number, are compared. In Fig. 3 the relative peak sound pressure level (normalized by that produced by the stationary laser source on the main lobe) is displayed as a function of the Mach number of the source as perceived by the hydrophone; M is the source Mach number and θ_0 and ϕ_0 the angles from the point of intersection of the laser beam with the water surface at the starting instant, to the receiver. Also shown in Fig. 3 are typical measured waveforms at various source Mach numbers. Even at source velocities for which there is significant disagreement in level between theory and measurement, these measured waveforms are in reasonable agreement with the predicted waveforms. It was found experimentally that by moving the source at transonic velocity, a gain of about 20 dB could be expected, and a very strong broadband pressure transient was generated. A sound pressure level of 152 dB re 1 μPa at 1 m was measured for such a Mach wave. The theoretical model predicts that in the vicinity of Mach 1, diffraction effects become predominant and actually tend to reduce the efficiency of the process. Although diffraction effects were clearly observed around Mach 1, it is not fully understood why the theoretical model underestimates the measured level. A possible explanation is that nonlinear effects, such as the temperature dependence of the thermodynamic coefficient β, become important and cannot be neglected.

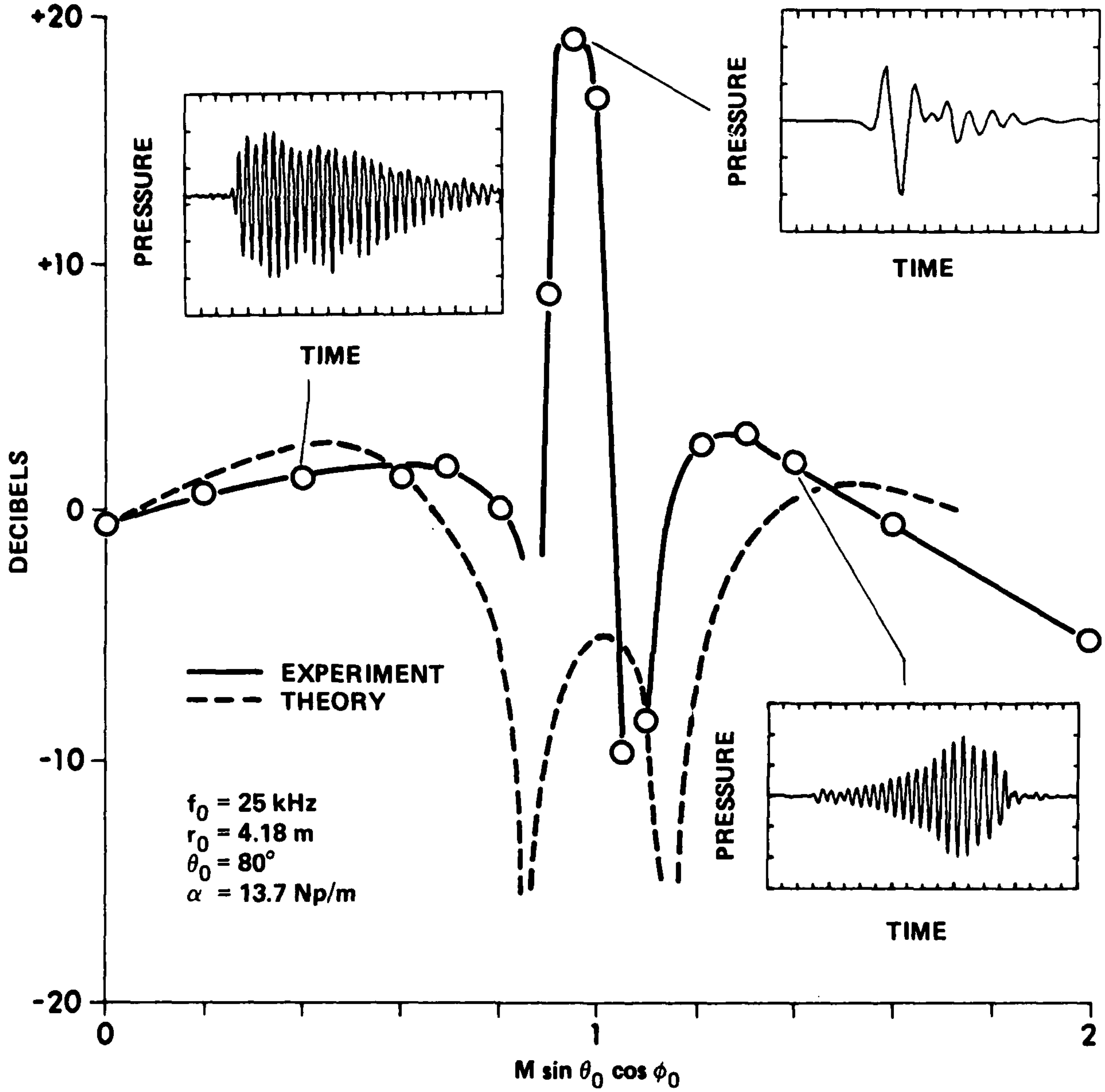

FIGURE 3
RELATIVE SOUND PRESSURE LEVEL versus MACH NUMBER

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D. Conclusions

The surprisingly high thermoacoustic levels measured at transonic source velocity indicate that, at least for sonar applications, future work should focus on laser induced Mach waves. It has been suggested[2,15,18] that the acoustic disturbance generated by a transonic thermoacoustic source is identical to the one generated by a stationary source of the same optical energy but delivered in an extremely short pulse. Although this is approximately true for an observer very far from the source, there is still a major advantage in using a moving source instead of a stationary source: The region of the medium which absorbs the heat produced by the laser beam is spread over the laser path length, whereas in the case of a stationary source it is localized to the laser beam cross section. This means that the maximum energy density acceptable before surface evaporation or explosive boiling occurs in the medium is much higher in the case of a moving source than for a stationary source.

There are several contrasts which should be noted between the thermoacoustic mechanism of laser sound generation and other mechanisms such as surface evaporation, explosive boiling, or optical breakdown. Although these other mechanisms are intrinsically more efficient than the thermoacoustic mechanism,[5,19-21] they cannot produce narrow directional sound beams. Moreover these energy conversion mechanisms are still not very well understood. The strongest acoustic signal that can be generated by a moving thermoacoustic source occurs when the laser beam is moving at transonic velocity. However, it should be emphasized that in this case the recorded acoustic signal has a very short duration so that the information content in the signal is limited. Also the high frequencies of such a pulse are attenuated very quickly in the water as the signal propagates. This problem might be overcome by finding judicious ways of depositing the heat source in the medium.

A possible design, which has been investigated in detail both theoretically and experimentally by Soviet physicists,[22] consists of using a stationary laser source delivering a periodic train of very short laser pulses, separated in time by an arbitrary delay T_0. This is achieved, for instance, by Q-switching the laser source.

In this design, a strong and directional acoustic disturbance of main frequency component $1/T_0$ is expected to propagate at long distances underwater. As shown in Ref. 22, this design increases the thermoacoustic intensity by a factor of about four over that of a standard monochromatic modulation system. However, the upper limit of the energy density acceptable to stay within the range of the thermal mechanism of sound generation is limited by the fact that the source is stationary.

A more sophisticated design has recently been suggested by Pierce and Hsieh.[23] It consists of splitting the laser beam into several beams, separated by an arbitrary distance L on the surface of the water, and all moving at a slightly supersonic velocity. The theoretical analysis, which is based on a general acoustic pumping principle,[24] predicts that this configuration allows a strong quasi-plane wave of main frequency component c/L, where c is the speed of sound, to propagate far under water in a collimated beam. The motion of the source would allow high electromagnetic energy levels to be deposited into the water, within the range of the thermoacoustic sound generation mechanism, and without surface evaporation or explosive boiling deteriorating the directional properties of the sound beam. At sufficiently high energy levels, which would produce other mechanisms if the source were stationary, nonlinear effects due to the temperature dependence of the thermodynamic parameters, i.e., the bulk coefficient of thermal expansion and the specific heat at constant pressure, could even enhance the thermoacoustic conversion efficiency.[25] The experimental investigation of such a design seems to be the logical extension of the work on laser thermoacoustic sources. If experimental results confirm the usefulness of this design, it would certainly place thermoacoustics within the range of some sonar applications.

Laser performance is of course a determinant factor in the capabilities of a thermoacoustic sonar. Fortunately, laser technology has improved considerably over the last two decades, and it is expected to continue in the near future. It is now possible to find pulsed solid state lasers that emit a single pulse of several hundred joules over several milliseconds.

Another type of laser that may be suitable for some underwater applications of thermoacoustics is the fairly new excimer laser.[26] This laser delivers short

pulses (4-50 ns) in the ultraviolet spectrum (0.18-0.3 mm) at a high repetition rate, so that high mean powers are achievable. The optical frequency can be downshifted to wavelengths suitable for thermoacoustic purposes (0.5-1 mm) by a efficient method known as the stimulated Raman scattering. Moreover these lasers are reliable, easy to operate, and pure, and they can produce a small beam diameter so that high energy densities can be produced fairly easily. However, the pulse duration is too short to take advantage of any motion of the source.

Infrared lasers such as the CO_2 laser, or the NH_3 laser, are among the most efficient CW lasers. In certain applications, the CO_2 laser can deliver up to 500 kW continuous.[27] Unfortunately the spectral region of these lasers is too far away from the region of interest for thermoacoustic applications. (Stimulated Raman scattering may be used only to increase the lasing wavelength, not to decrease it.)

However, recent developments on chemically pumped lasers seem to indicate[28] that a continuous high power laser of wavelength 1.3 mm could be developed, and this laser would certainly be perfectly suitable for underwater applications of thermoacoustics.

In summary, it seems that the laser technology is improving so rapidly that, in the not too distant future, a laser-induced sonar could conceivably be designed based on the principles of thermoacoustic generation of sound.

III. FEASIBILITY STUDY OF THE MOVING THERMOACOUSTIC ARRAY

A. Introduction

A feasibility study for sonar applications was carried out in parallel with the basic study described in the previous section. While the MTS possessed many useful attributes, the main obstacle to practical sonar applications is its low efficiency in converting optical energy to acoustic energy. The existing claims regarding its efficiency are reviewed as follows.

In 1976 the process was investigated theoretically and experimentally by Muir, Culbertson, and Clynch[12] for the case of a stationary source. The acoustic energy produced by the thermoacoustic array through the thermoacoustic conversion process (with any reasonable quantity of optical energy) was found to be small, several orders of magnitude smaller than that produced by conventional acoustic sources under equivalent operating conditions. Lyamshev and Sedov[29] in a very comprehensive review paper state that "under the conditions of thermo-optical generation of sound the conversion efficiency attains at best 10^{-5} to 10^{-6}." Thus thermoacoustic conversion efficiency must be significantly increased before the thermoacoustic array can be considered as a viable acoustic source for marine applications. There have been several recent Soviet papers on the subject that have made diverse claims, particularly with regard to the MTS. The simplest case is that of an MTS traveling in a straight line. One way of producing an MTS is to use a rotating mirror to deflect the laser beam and scan it over the surface of the water as shown in Fig. 1. It was suggested by some that the MTS can give significantly higher conversion efficiencies. Bozhkov et al.[14] claim that the moving thermo-optical sources are "highly directional sound sources with a tunable frequency and of considerably higher efficiency than stationary sources." In an earlier publication, Bozhkov et al.[30] also claimed that "the given method of sound generation affords a realistic possibility for the creation of powerful short pulses with a high frequency carrier." The case of an MTS executing various types of motion, including oscillatory motion, has been studied by Lyamshev and Sedov,[18] but they claim only that the efficiency of moving sources is "practically the same as for a stationary source." It is against this background of diverse and conflicting

claims regarding the performance of the MTS that the present investigation took place.

B. Achievements

The thermoacoustic conversion process was analyzed from basic principles.[2] A frequency domain approach was used which is complementary to the time domain approach used in the basic study by Busch-Vishniac and Berthelot. Unlike other existing frequency domain analyses,[10-12,29] the formulation used here gives valid solutions at all velocities of the thermoacoustic source including the sonic case. Using this approach, both the stationary and moving cases were examined. The theoretical results were analyzed to determine the merits of an MTS as opposed to the stationary thermoacoustic array, and the thermoacoustic energy conversion efficiencies were compared. The influence of the optical signal waveform and the acoustic signal frequency on the conversion efficiency was examined, and then the energy conversion efficiency upperbounds were established. The directivity inherent in the Doppler distortion was examined. Numerical examples were used to illustrate the performance of the thermoacoustic source, particularly the angular resolution afforded by the directionally dependent Doppler shift and the range penetration under typical oceanic conditions. The theoretical results are supported by experimental measurements. The investigation was reported as a technical report.[2]

C. Conclusions

One important issue concerns the efficiency of the thermoacoustic energy conversion process, and particularly whether the MTS was more efficient than the stationary source. The efficiencies were theoretically analyzed. In the nonsonic case, that is, when resolved velocity of the MTS in the direction of the receiver is not equal to the speed of sound, the acoustic signal energy density at a given point in the medium is a function of the rate of change of the optical power delivered to the water. However, since the optical power flow from the laser beam to the water is unidirectional and irreversible, a prescribed amount of energy must be delivered in order to allow the necessary power changes to take place. This contrasts with

the sonic case, in which the functional form of the optical signal has no influence on the acoustic signal, which is determined purely by the total optical energy, the physical properties of the medium, and the geometrical configuration of the array. In all cases the total optical energy sets the upper bound of the total acoustic energy spectral density that can be produced at a given range from the thermoacoustic source. Thus, the upper bound of the thermoacoustic energy conversion efficiency was derived. From the theoretical efficiency analysis, the MTS was found to be, at any speed, neither more nor less efficient than the stationary thermoacoustic source of the same dimensions and optical energy.

Factors which critically influenced the thermoacoustic conversion efficiency were examined. The thermoacoustic conversion efficiency upper bound was found to increase with acoustic signal frequency and optical input energy. Estimates of the conversion efficiency upper bounds, as a function of optical input energy and signal frequency, for both the moving and stationary thermoacoustic sources, are shown in Fig. 4. The conditions for achieving the upper bound, thus obtaining the theoretical maximum output, were examined. Conditioning of the optical input signal was examined and it was found that the impulse train is the most efficient optical power waveform for the thermoacoustic generation of acoustic energy.

Although the MTS is no more efficient than the stationary thermoacoustic array, it does have one significant advantage: Since it is a moving source, the Doppler shift of its signal is inherently direction dependent. This property may be used for direction finding. Since it is possible to achieve extremely high velocities, much higher than that achievable with transducers that have to be in contact with the water, the potential angular resolution is high. The direction dependent Doppler shift of the acoustic signal gives the MTS a unique property which is potentially useful for direction finding without the use of a conventional beamformer.

In the laboratory, where propagation distances are short and operating frequencies are high, the thermoacoustic array can be very useful, particularly because of its noncontact property and wideband capability. For underwater applications such as sonar, where the propagation distance is a few hundred

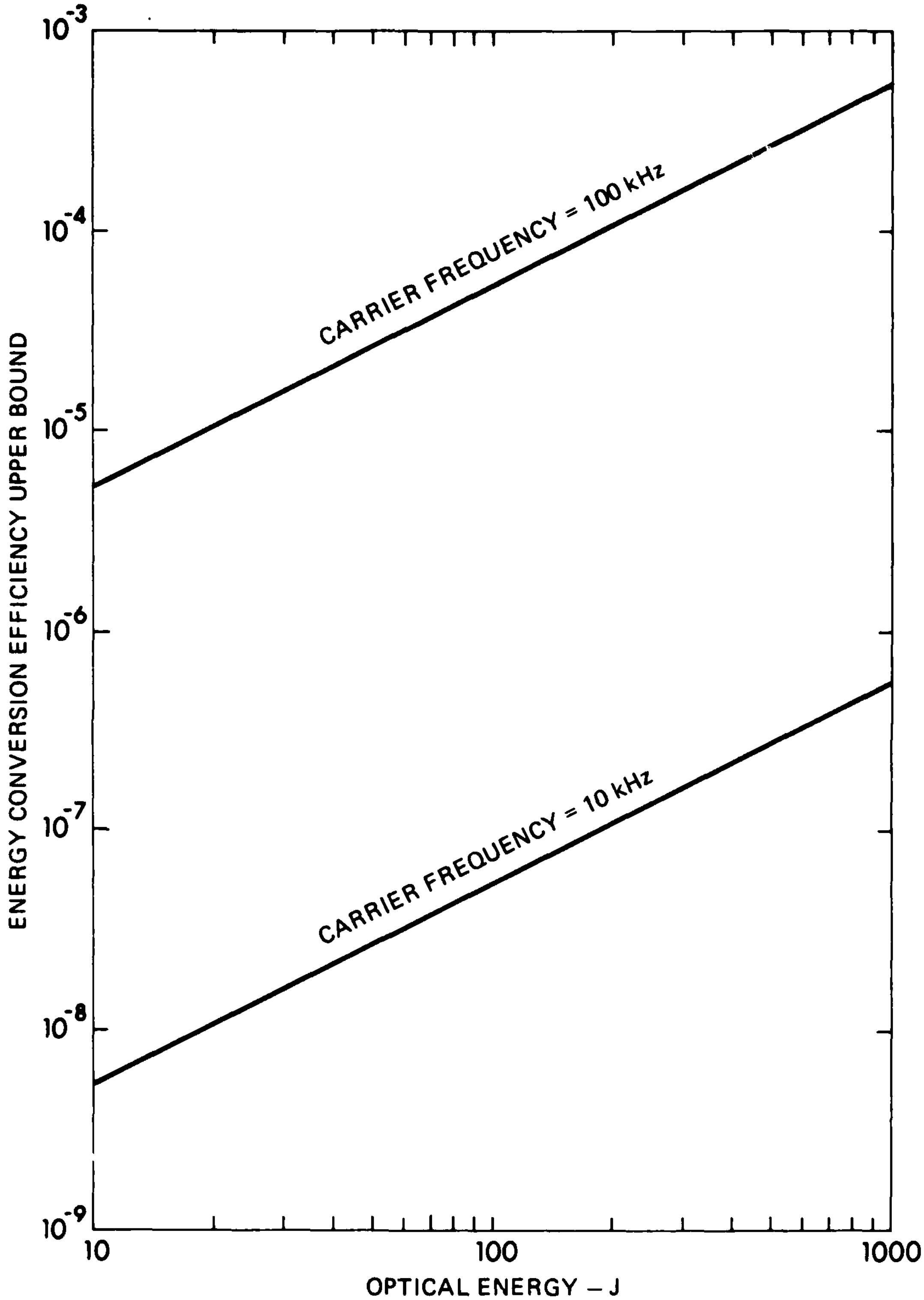

FIGURE 4
ENERGY CONVERSION EFFICIENCY UPPER BOUND IN SEAWATER AT A TEMPERATURE OF 10°C

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meters or more and where acoustic frequencies below 100 kHz must be used to avoid excessive absorption loss, the efficiency upper bound is extremely low for practical values of optical energy and acoustic carrier frequency. Therefore a more efficient optoacoustic conversion process is required.

These findings contrast sharply with some of the published results.[14,30,31] The following are two possible reasons for why the discrepancies exist.

The first reason concerns the assumptions that are normally taken for granted when measuring transducer efficiency. When comparing the efficiencies of transducers, it is necessary to define the desired operating conditions and then measure their efficiencies under the same conditions. One important aspect of the operating conditions is the acoustic signal itself. For conventional transducers, valid comparisons can be made if the input signals and the other relevant operating conditions are the same, because the output signal is normally a reasonable replica of the input signal. This, however, is not the case for an MTS because of the enormous Doppler distortion that it can produce, distortions far greater than conventional contact transducers can ever achieve. Therefore, an effort must be made to generate the same acoustic signal before any meaningful efficiency comparisons can be made. There are instances[31] where, when comparing conversion efficiencies, the acoustic signal was allowed to change with the velocity of the MTS while the optical input signal was kept constant. It was then concluded that the efficiency of an MTS was higher than that of a stationary thermoacoustic array. The conclusion should have been that the efficiency varied as a function of the frequency of the acoustic signal. This oversight is an easy one to make, since certain assumptions that one normally takes for granted are not valid for moving sources.

The second reason concerns the benefits derived from the redistribution of the laser energy. In the case of the claims by Berthelot[1] and Bozhkov,[14,30] the argument used, as reproduced from the latter reference, runs as follows. "The efficiency ... increases directly as the laser intensity. For a stationary source, ... laser intensity is limited by boiling of the liquid in the heating zone. In the case of

the moving source the heat absorbed in the liquid is distributed in space, whereupon the ultimate value of the light intensity and, hence, the ultimate efficiency of energy conversion is greater ... than for a stationary source." It should be noted that it is the energy density that is limited by the boiling point and not the intensity. However, in the case of water, there is an incentive to get as close to the boiling point as possible without actually causing the liquid to boil because the coefficient of expansion, which directly governs the conversion efficiency, increases with temperature. Furthermore, should the laser energy density, for any given beam diameter, be greater than that which is consistent with maximum efficiency without boiling, it is possible to control it by spreading the energy over a larger volume rather than by moving the source. This may be done by fanning out the laser beam in a direction perpendicular to the desired acoustic beam axis. This is equivalent to producing a planar array.

There is doubt that the MTS will be sufficiently efficient for underwater sonar applications; however, there are alternative mechanisms of optoacoustic sound generation which should be explored in order to find more efficient processes.

IV. THEORETICAL STUDY OF THE NONLINEAR OPTOACOUSTIC PROCESS

A. Introduction

The thermoacoustic process is only one of several mechanisms for converting optical energy into acoustic energy. The thermoacoustic process is often referred to as the linear process. It is linear in the sense that, over a large range of temperatures, the change in density of the water is linearly proportional to the optical energy input, at least for small input energy densities. Other processes by which optical energy is converted to sound are grouped together under the name nonlinear processes. The current knowledge regarding nonlinear processes was thoroughly reviewed by Lyamshev and Naugol'nikh.[25] Nonlinear processes, in general, have been found experimentally to be more efficient than the linear process, but they are not well understood.

The anatomy of the main nonlinear processes is illustrated in Fig. 5. The main processes include: weak and strong evaporation, optical breakdown of the vapor, and optical breakdown of the liquid. They are mainly governed by the intensity and energy density of the laser pulse. Evaporation processes are mainly governed by energy density. Weak evaporation refers to the evaporation of a thin surface layer of the liquid, while strong evaporation refers to explosive bubbling from the surface and from the interior of the liquid.

At low laser energy densities and low intensities, the optoacoustic conversion is through the thermoacoustic process. Going from point A towards point B in Fig. 5, in the increasing energy density direction, the thermoacoustic process gradually gives way to the evaporation process. Evaporation processes can take place only when the energy absorbed is equal to or greater than the specific internal energy requirement for the phase change. The absorbed energy is directly governed by the delivered surface energy density and by the absorption coefficient. For 1.06 μm laser radiation, the absorption coefficient is normally about[12] 15 m^{-1}, which gives a surface energy density threshold of approximately 2×10^7 J/m^2.

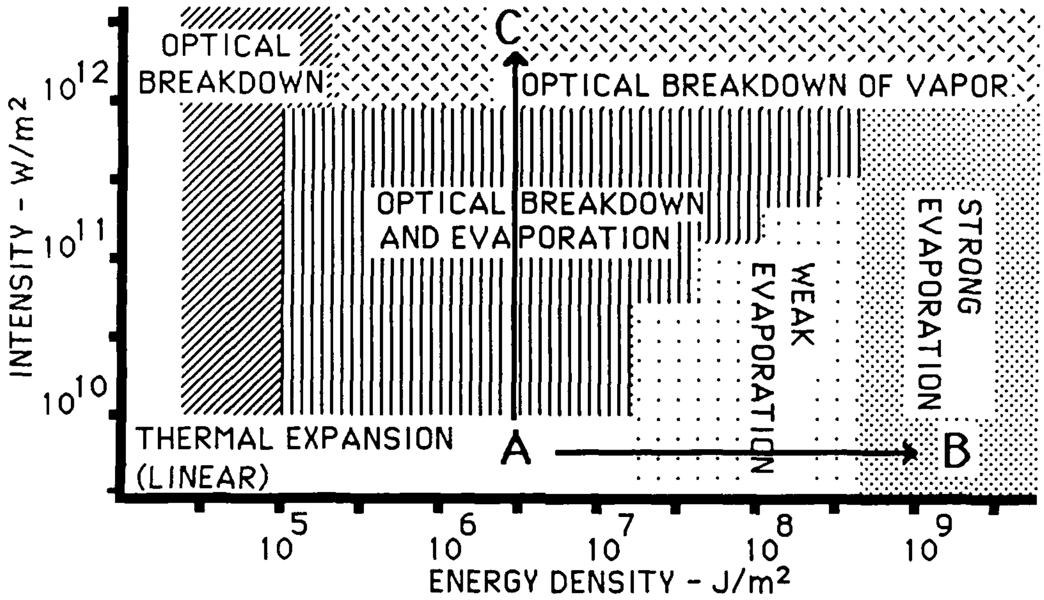

FIGURE 5

THE ANATOMY OF OPTOACOUSTIC SOUND GENERATION IN WATER WITH A 1.06 μm Laser

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Going from A towards C in Fig. 5, in the increasing intensity direction, the thermoacoustic process will abruptly give way to optical breakdown processes. Above certain intensity and energy density thresholds, optical breakdown causes the physical properties of the medium to change. The intensity threshold for breakdown of water is strongly dependent on impurities such as suspended particles. For 1.06 μm radiation, water becomes drastically more opaque. This is equivalent to a sudden increase in the absorption coefficient and a consequent reduction in the evaporation threshold. For 10.6 μm radiation on water, optical breakdown of the ejected vapor has been observed[32] above a threshold of 2×10^{12} W/m^2. Of course, there must also be sufficient energy density to produce the vapor in the first place; therefore there is an energy density threshold as well.

Sound generation is by a combination of two main physical processes, the expansion of the material within the liquid due to physical or chemical changes and the recoil pressure at the surface from the ejected vapor. There have been a number of publications on this topic. A large proportion of the reported works have been for cases where most of the energy is spread over several megahertz.[33,34] The results reported by Hickman[35] were in the range of sonar frequencies but the experimental conditions were imprecise. The most extensive set of results were reported by Maccabee and Bell.[32,36-38] Their data covered a wide range of operating conditions. Their results showed significant finite amplitude distortion and extra attenuation of the acoustic pressure. Maccabee and Bell used a "rocket" model to predict the blast pressure and linear superposition to construct the acoustic pressure. They found that the model predictions were not consistent with the experimental results.[38] One likely contributor to the discrepancy is the nonlinear propagation of the acoustic output, because they used laser pulses of very high energy densities and intensities.

B. Accomplishments

The optoacoustic process being considered here is specifically that of dielectric breakdown, followed by a phase change from liquid to gas and the explosive expansion of the gas. The initial dielectric breakdown and phase

change are not expected to significantly contribute to the sound generation process, but they will consume a certain amount of energy. This may be considered as an overhead requirement. The explosive expansion is believed to be the main mechanism of sound generation. It was modeled as a blast reaction. The blast model used is based on the work of A. N. Pirri[39,40] who successfully modeled the momentum transfer from a high powered laser blast to the surface of a solid. The model is general enough to be adapted to give a first approximation of the acoustic signals produced by a laser induced blast at the water surface. Our model is based on the more complicated of the two Pirri models, the two-stage model. It has a one-dimensional stage where the blast front is assumed to rise vertically from the surface. This stage is essentially the "rocket model" used by Maccabee and Bell.[38] The second stage is a two-dimensional spreading regime where the blast expands outwards over the surface. The model is illustrated in Fig. 6. The sound is assumed to propagate linearly and the underwater acoustic pressure signal is constructed from elementary constituents by linear superposition. In a theoretical study without experimental verification, Wu[41] followed this approach and obtained an estimate for the acoustic pressure. The deformation of the water surface is assumed to be negligible. The linear propagation and negligible deformation assumptions are some of the main shortcomings of this model. Nevertheless, under operating conditions where these assumptions are approximately valid, the model is expected to produce useful results. With further theoretical analysis supported by experimental measurements, more realistic models will evolve. Experiments were carried out to verify the blast model and to obtain a better understanding of the process. Due to the small amount of time and resources available at this stage of the project, these investigations should be considered as preliminary. In these experiments, the specific goals are (1) to measure the energy density overhead, (2) to compare the predictions of the blast model with the practical results, and (3) to identify weaknesses in the blast model. From these results, recommendations for future work have been made.

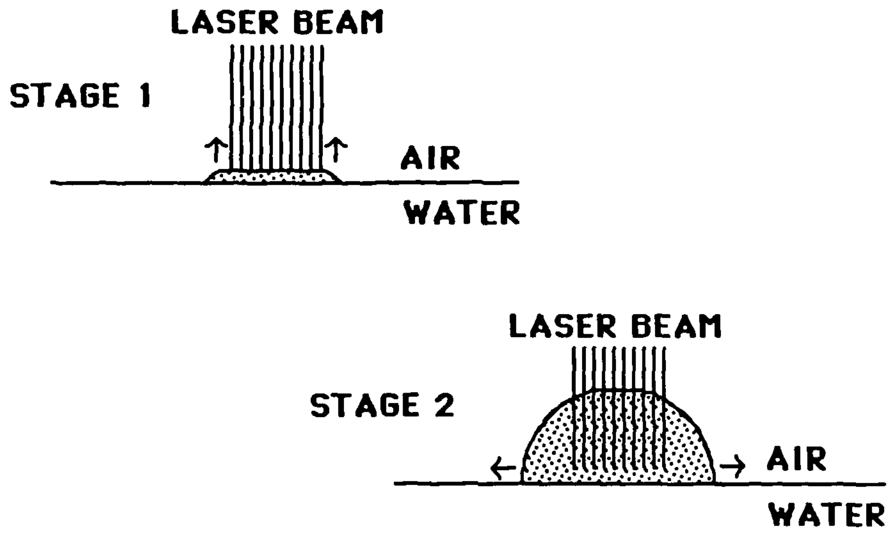

FIGURE 6

PIRRI'S SECOND BLAST MODEL

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C. Conclusions

A nonlinear process of optoacoustic sound generation was modeled. The process was one of inducing an explosive reaction at the water surface. The explosive reaction is induced by using a high intensity pulse. The experimental results suggest that the sequence of events might be as follows: The leading edge of the laser pulse causes a phase change, most probably a dielectric breakdown, within a thin surface layer. It was found that 16.25×10^3 J/m^2 was required to produce the phase change. As a result of the dielectric breakdown, the layer turns opaque and the remaining laser energy is absorbed by it. Since the layer is very thin, the absorbed energy causes explosive expansion and evaporation of the layer. Bearing in mind that this is only a first attempt, the model gave estimates of the acoustic output signal which were in reasonable agreement with our experimental results as well as some of those of Maccabee,[38] as shown in Fig. 7. The signal levels predicted were approximately consistent with the measured data.

There were a number of discrepancies between theory and experiment. The shape of the signal spectrum as predicted by the theory did not match the measured spectrum. The most probable cause is the assumption in the model that the laser pulse is rectangular, while the actual laser pulse in the experiment was more rounded with a short rise time and a much longer fall time. The measured upper cutoff frequency in the diffraction loss limited case was significantly higher than the corresponding model prediction. This is believed to be due to the deformation of the water surface which is neglected in the current model. In conclusion, a successful first attempt has been made to model a nonlinear optoacoustic sound generation process. This model should be further developed to give a more accurate representation of the process and thus provide a better understanding of its physics.

D. Future Plans

Improvements are planned in both the theoretical model and in the experimental apparatus.

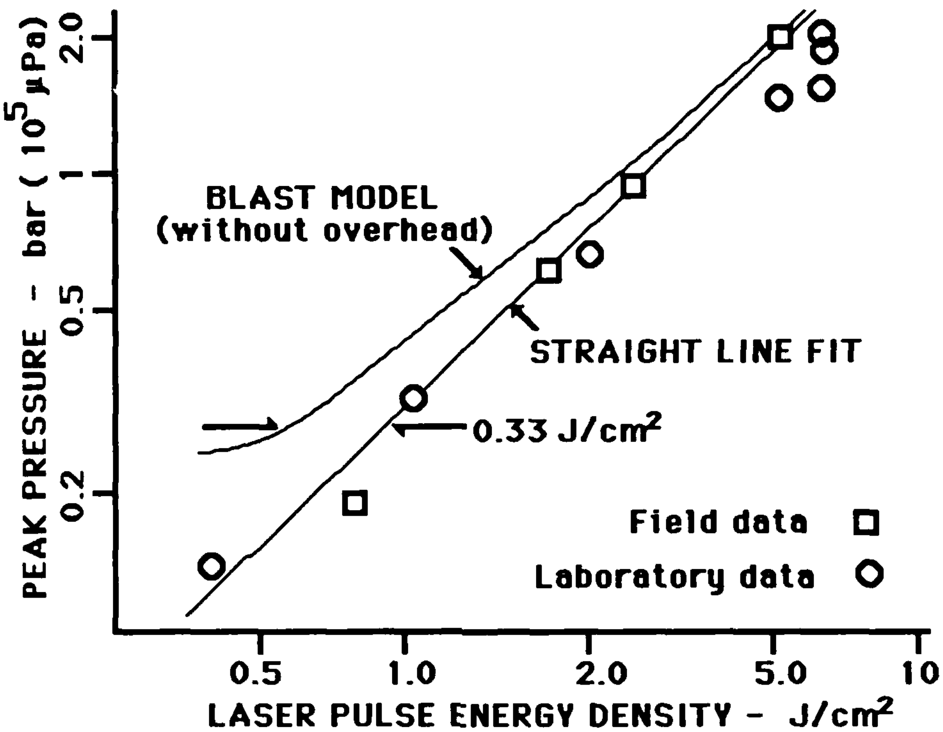

FIGURE 7
COMPARISON OF THEORETICAL MODEL PREDICTIONS OF PEAK PRESSURE WITH THE EXPERIMENTAL DATA FROM MACCABEE AND BELL

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The theoretical model needs to be improved in several respects. The experimental results indicated that a portion of the laser energy may have been used to produce a physical change within a thin layer of the water before a blast can be generated; this needs to be verified by a quantitative theoretical analysis. The experimental results obtained so far indicate that the shape of the laser pulse and the deformation of the water surface are important; therefore the model should be modified to take these into account. Consequently, a model for the deformation of the water surface is also required. Photographic data[33] suggest that there is a spherical indentation of the surface due to the formation of a gas bubble. Finally, to extend the validity of the model it is necessary to include nonlinear propagation effects using a numerical method such as that of Hall and Holt.[42] Their method uses finite element analysis in a dynamic frame of concentric elements.

From our experience in the laboratory, a number of improvements in the experimental apparatus are required to provide a more complete set of data. An optical fiber system to detect laser light above and below the water line is required to monitor the history of the blast and verify the model of the blast process. Particularly, this will allow us to determine when the surface has reached a state of dielectric breakdown. It may also allow the scattering of the laser light by the blast to be studied. A better hydrophone, with a wider band, say from 1 kHz to 10 MHz, is required. For this application, commercially available shock probes may suffice. Finally, to keep up with the increased data rate, the data acquisition needs to be upgraded to handle sampling rates of at least 10 million samples per channel per second.

The above improvements in the theoretical model and the experimental apparatus will enable us to investigate the nonlinear optoacoustic processes in greater depth. We will be able to observe the formation of the blast with acoustic and optical sensors. With the optical sensors, we will determine the proper sequence of events of the blast process and with the acoustic sensors their contributions to the acoustic output. The process is expected to be complicated by oscillations of the gas bubble, which is formed as a by-product of the blast. When the process is understood with sufficient precision, then it would be possible to

make estimates of its optoacoustic energy conversion efficiency, particularly in the band of useful sonar frequencies.

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